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EFFECTS OF COMBUSTION CHAMBER BLOCKAGE ON BLUFF BODY FLAME STABILIZATION

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EFFECTS OF COMBUSTION CHAMBER BLOCKAGE ON BLUFF BODY FLAME STABILIZATION

Thesis by

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Lieutenant, United States Navy

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ABSTRACT

The necessity for stabilizing a flame in a high speed flow of combustible gas has led to extensive studies of the mechanism of flame stabilization by bluff bodies. As a result of these studies it has been found that the stability limits depend directly on a characteristic wake length and that under certain conditions this characteristic dimension depends on the square root of the flame holder scale.

In the present investigation the geometry of the flame in the stabilization region is examined by means of photographic and probing techniques. The results of the studies show conclusively that for a constant blockage ratio, the wake geometry scales linearly with flame holder size. The observed square root dependence of the characteristic wake length, and hence of the blowoff velocity, is shown to be directly caused by blockage effects.

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LIST OF SYMBOLS

C_p	base pressure coefficient $C_p = \frac{P_b - P_s}{P_t - P_s}$
D	cylindrical flameholder diameter
H	height of duct (combustion chamber)
D/H	blockage ratio for cylindrical flameholder
L	length of recirculation zone
P_b	pressure at downstream stagnation point of flameholder
P_s	static pressure in uniform flow upstream of flameholder
P_t	total pressure in plenum chamber
Re	Reynolds number based on approach gas speed and flameholder diameter
U	gas speed past the flame
U_{bo}	gas speed past the flame at "blow-off"
V	approach gas speed
V_{bo}	approach gas speed at "blow off"
W	width of flame front
x	distance from flameholder reference plane measured downstream
ϕ	fuel-air equivalence ratio, fraction of stoichiometric

I. INTRODUCTION

In ramjet engines and turbojet afterburners, it is necessary to provide for continuous ignition of a fast moving burnable gas mixture. Since the gas speed greatly exceeds the normal burning velocity in the mixture, the combustion process must be maintained, or "held", within critical physical engine boundaries by artificial means. Such a flame stabilization process has been achieved in practice by placing a bluff body in the combustible gas stream and igniting the mixture with the hot gases that recirculate in the wake. Many investigations have been conducted to determine the mechanism of the flame stabilization and to determine the important parameters of this method of maintaining combustion in a high speed gas stream.

Early experiments by Nicholson and Fields (Ref. 1), Longwell (Ref. 2), Scurlock (Ref. 3), and Haddock (Ref. 4) have shown that flame stabilization in the wake of a bluff body is possible over a useful range of fuel-air mixture ratios and approach gas speeds. These experiments also indicated that the immediate wake of a bluff body flame holder, i.e., the region responsible for the ignition process, may be divided into two distinct regions: the mixing zone and the recirculation zone, (Cf. Figure 1). Nicholson and Fields (Ref. 1) showed that the recirculation zone, or eddy region, extends an appreciable distance downstream. The average gas speed inside this recirculation zone has been found to be quite small compared to the approach stream velocity, and the temperature in the zone has been found by Zukoski (Ref. 5), and Wright (Ref. 6), to be very near the adiabatic flame temperature. The mixing zone is a turbulent region

in which cool combustible material mixes with hot recirculation zone gas. Under ordinary operating conditions this zone is turbulent; however, Zukoski (Ref. 7) has shown that a transition occurs near Reynolds numbers of the order of 10^4 and that below this point the mixing zone is predominantly laminar. Wright (Ref. 8), Longwell (Ref. 9), and Westenberg (Ref. 10) have determined by chemical sampling that the chemical reaction takes place largely in the mixing zone at the edges of the wake and that the recirculation zone gas consists almost entirely of products of combustion.

One characteristic of the flame stabilization process which is of primary engineering importance is the maximum approach gas velocity, for a given fuel-air mixture ratio, at which the combustion process can be maintained. Zukoski and Marble (Ref. 5) have recently found experimentally that, for a fixed fuel-air ratio, the gas speed past the flame is directly proportional to the length of the recirculation zone. This result is in agreement with following picture of the stabilization mechanism: Ignition of unburnt material in the mixing zone is effected by mixing of the hot recirculation zone material with the incoming mixture. Ignition will occur if the residence time of the material in the mixing zone is sufficiently long. However, as the gas speed past the flame is increased, the residence time is reduced and a condition will be reached such that the flame will blowoff. For similar flameholders, the residence times at blowoff will be equal, and therefore, the ratios of recirculation zone lengths to gas speeds must also be equal. Hence, the length of the recirculation zone will be proportional to the gas speed past the flame. (Note that the velocity in this correlation is the gas speed past the flame rather than the approach

gas velocity.)

Thus, the recirculation zone length is an important parameter of the stabilization process. One of the unexplained results of earlier experimental work was that, under certain conditions, the recirculation zone lengths and blowoff velocities scale as the square root of the characteristic flameholder dimensions. This result was found to hold for such bluff bodies as circular cylinders and "V" gutters (Refs. 3 and 4). Since the mixing zone was turbulent for the Reynolds number range of interest in these experiments, a linear dependence rather than a square root dependence may be expected.

The general purpose of the present investigation was to determine the scaling laws applicable to that part of the wake which is important in the stabilization process. In particular, it was hoped that this investigation would explain the observed square root dependence of the recirculation zone length and blowoff velocity on the flameholder size.

The present work was principally concerned with a study of the geometry of the flame stabilized in the wake of bluff body flameholders. The flame spreading rate and the length of the recirculation zone were the principal geometrical variables investigated. The flame width downstream of the flameholder was measured as a function of approach gas velocity, fuel-air ratio, flameholder diameter, and blockage ratio. Circular cylinders were used primarily as flameholders with representative experiments on other shapes conducted to determine the effects of flameholder shape on the flame geometry.

Base pressure coefficients were investigated in an effort to associate the observed flame spreading rate with the fluid dynamic variables of the problem.

Recirculation zone lengths were measured by a flow tracer technique to determine the effect on the length of the zone, and consequently the effect on blow-off velocity, of variations in flameholder diameter and blockage ratio.

The results of the experiments show conclusively that the observed square root dependence of recirculation zone length on cylinder diameter is due to variation in blockage ratio, and that for constant blockage ratio the recirculation zone, and hence the blowoff velocity, will scale linearly with flameholder size.

II. EXPERIMENTAL APPARATUS

A schematic diagram of the basic flow systems used in this investigation is shown in Figure 2. The apparatus is made up of the air supply and control system, fuel, ignition, and measurement systems.

A controlled quantity of air was drawn from a well-regulated supply and heated to a fixed temperature by passing it through a heat exchanger system. The hydrocarbon fuel was injected into the heated air stream a sufficient distance upstream of the plenum chamber to provide a uniform homogeneous gas mixture flowing into the plenum chamber. A smoothly converging nozzle connected the plenum chamber to the combustion test duct, the contraction ratio of this convergence being sufficient to give uniform flow into the combustion duct.

The test section was a rectangular combustion chamber with 2" x 4" cross section. Vycor glass windows, interchangeable with water-cooled metal walls, allowed visual and photographic observation of the flame for a distance of 5" downstream of the flameholder when desired.

Air Supply and Control System

The air supply for combustion was furnished by two reciprocating pumps with combined capacity of 3.7 lbs./sec. at a pressure of 100 psi. The rate of mass flow was regulated by a remote controlled sonic-throat valve located upstream from the heat exchanger and fuel injector, allowing control of air flow independent of variations in fuel flow rate, mixture temperature, and combustion chamber static pressure.

The mixture temperature was controlled by heating a shunted portion of the air in a shell-and-tube type heat exchanger using a turbojet can burner with separate air supply and exhaust as the tube heating element. Two butterfly valves operated by a commercial control system fixed the amount of air passing through the heat exchanger, and thus the mixture temperature. For this investigation it was desired to eliminate mixture temperature as a variable in the test; thus, for all runs, the mixture temperature was maintained as constant as possible at 610°R, the minimum temperature which safely insured complete vaporization of all fuel components.

Fuel System

The fuel used in these experiments was Union Oil Thinner No. 1 whose detailed specifications are given in Reference 11. This gasoline-type fuel was used because of its uniform chemical properties and abundant supply. The fuel tanks were pressurized to 100 psi by use of nitrogen pressure bottles, and the fuel was injected through a constant pressure variable area nozzle 30 feet upstream from the plenum chamber.

Ignition System

Ignition was initiated for each period of combustion by producing a high voltage spark between a remotely positioned ignitor rod and the surface of the flameholder. A 10,000 volt power supply provided a sufficient spark across approximately a 1/8 inch gap when the ignitor rod was positioned to produce ignition for stoichiometric mixtures at flow velocities up to about 150 ft./sec.

Plenum Chamber and Nozzle

The plenum chamber was a 15 inch diameter pipe section 5 feet long as shown in Figure 2. To break up the high speed air stream entering the plenum chamber, an 8 inch diameter perforated baffle plate was positioned just upstream of the chamber and 6 stainless steel 200 mesh screens were located at 6 inch intervals inside the chamber to reduce the turbulence of the mixture entering the nozzle. A 12 inch diameter rupture diaphragm was provided in the side of the plenum chamber at the upstream end to allow quick reduction of pressure in the event of blow-back into the plenum chamber; however, no such occurrence was experienced during this investigation.

The nozzle was 18 inches long and reduced the cross-section from a 15 inch diameter circle to a 2" x 4" rectangular opening for a contraction ratio of approximately 22:1. Pressure surveys of the nozzle showed a flat velocity profile entering the combustion duct for all operating conditions.

Combustion Chamber

The combustion chamber was a 2" x 4" rectangular flow passage 9 inches long. It was constructed of cold rolled mild steel and was water-cooled, as shown in Figure 3, to prevent deformation and to allow relatively constant boundary conditions on the flame. The flameholders were mounted through 1/8 inch holes across the center of the duct as shown in Figure 2, mounted across either the 2" or 4" dimension. This allowed two area blockage ratios for each size flameholder. Uncooled Vycor glass walls were used on all four

sides of the duct for the runs requiring visual and photographic observation. The glass windows allowed observation from just upstream of the flameholder to a position 5 inches downstream. As shown in Figure 3, the last 1.5 inch exit portions of the combustion chamber walls were film cooled. Tolerances between the windows and supporting wall surfaces were made less than 0.002 inches to minimize wall surface discontinuities. The combustion chamber exhausted into a cross water spray and film cooled steel exhause duct 24 inches in diameter located approximately 1 foot downstream of the combustion chamber exit.

Flameholders

The bluff body flameholders primarily used were hollow circular cylinders constructed of stainless steel tubing sealed at the ends except for 1/8 inch inlet and exit hollow mounting tubes used for mounting support, cooling passages, and pressure tap leads. The centers of the flameholders were located 7 inches upstream from the chamber exit on the centerline plane of the duct. Through-flow of water was sufficient to keep the downstream stagnation point of the flameholder nearly constant and well below 150°F during the runs. Some typical flameholders used in this investigation can be seen in Figure 4.

Pressure and Temperature Measuring Equipment

As indicated in Figure 2, plenum chamber total pressure and combustion chamber entrance static pressure were measured by water and mercury manometers. The plenum chamber total pressure was obtained from an ordinary total head tube located on the centerline of the plenum chamber downstream of the last calming screen. The

combustion chamber entrance static pressure tap was located on the centerline of one of the 2 inch wide walls, 3 1/8 inches upstream from the flameholder centerline.

Base pressure measurements were made by silver soldering a 1/32" diameter tube to the inside surface of the flameholder with 1/32" diameter pressure orifice drilled into the flameholder at the central downstream stagnation point. This pressure tube was led through the inside of the flameholder mounting to a water and mercury manometer and measured against atmospheric pressure.

A chromel-alumel thermocouple in the plenum chamber actuated a Brown Automatic Potentiometer to give a check measurement of the inlet mixture temperature.

Schlieren Equipment

The schlieren system used was a conventional double mirror type, using a BH-6 mercury vapor light source. The focal length of the two 6 inch diameter concave mirrors was 54 inches. The spark system was determined to have a spark duration of less than 7 microseconds and was synchronized with the camera shutter by a series of timing relays. The short spark duration was desired to prevent fogging of the film by light from the flame; super XX film was used for all photographs.

III. FLAME WIDTH

It is reasonable to assume that all geometrical parameters of the flame should scale in the same manner with respect to the characteristic dimension of the flameholder. Under this assumption it was felt that the flame width, measured at regular intervals downstream of the flameholder, would be a convenient method of determining the scaling relationship between flame parameters and flameholder size. Circular cylinders were used primarily as flameholders, with a "V" gutter used periodically to check the validity of the results for different geometrical shapes. The independent effects on the flame width of varying gas flow velocity, fuel-air ratio, flameholder diameter, and blockage ratio were determined.

Measured Techniques

The boundaries of the flame are defined as the locus of points at which the temperature of the gas mixture first begins to rise due to the influence of the hot wake. The initial temperature rise in the wake gases is rapid enough so that a schlieren photograph shows the boundary as a well defined line between hot wake gases in the mixing zone and cold incoming mixture.

Flame width measurements were made directly from full scale negatives (Cf. Figure 5), with measurement errors less than ± 0.01 inches. Misalignment of the schlieren system and three-dimensional density gradients in the flow give rise to measurement errors of no more than ± 0.02 inches. Thus, the overall error in measurements is no more than ± 0.03 inches, or approximately 5 per cent for the smallest measured width.

Effect of Approach Gas Velocity

Figure 6 shows the variation of flame width just downstream of the flameholder with variation of approach speed from 100 to 437 ft./sec. This data, shown for the 1/2" diameter circular cylinder, is typical of that obtained for all cylinders used, i. e., for cylinders varying in size from 1/8 inch to 1 inch in diameter. For this data, the fuel-air ratio was kept near the ratio for stoichiometric mixture.

This plot clearly shows that the flame width for the region investigated is independent of approach gas speed, for a speed range including both laminar and turbulent flow regimes.

Effect of Fuel-Air Mixture Ratio

Figures 7 and 8 illustrate the dependence of flame geometry on the fuel-air ratio for a 1/2 inch diameter circular cylinder; for this data, the approach gas velocity was kept constant. The data of Figure 8 shows that for values of fuel-air ratio other than those very near lean and rich blowoff, the flame width for a distance of 8 diameters downstream of the flameholder is essentially independent of the mixture ratio. However, for values of the fuel-air ratio near the blowoff conditions, the width tends to increase slightly. Similar results were found for all circular cylindrical flameholders used.

Near blowoff values of fuel-air mixture ratio, the noise level of the combustion process increases. Increase in the amplitude of longitudinal pressure waves in the duct may be responsible for the slightly greater flame width observed near blow off mixture ratios. The increase may also be associated with increased turbulence noted

at outer edges of wake near blow off conditions (Cf. Figure 7).

Effect of Flameholder Diameter and Blockage Ratio

Figure 9 illustrates the dependence of flame width on the flameholder size for 1/8, 3/16, 1/4, 1/2, and 1 inch diameter circular cylinders used as flameholders in the same duct. The curves given in this figure were obtained from data plots similar to that given in Figures 6 and 8, and covered a wide range of fuel-air ratios and gas speeds. In Figure 10, the flame holder diameter is used to normalize both wake width and distance downstream. From this plot it is evident that the flame width does not scale directly with the size of the flameholder, but rather that at a given distance downstream of the flameholder, W/D, decreases rapidly with flameholder diameter.

Because the circular cylinders are two-dimensional, the area blockage ratio, or ratio of frontal area blocked by the flameholder to the total cross section area of the duct, is just the ratio of flameholder diameter to duct height, i.e., (D/H).

In these experiments, since the combustion chamber height was kept the same, the blockage ratio D/H increased with increased flameholder diameter. As the blockage ratio is increased, it is reasonable to expect that the curvature of the streamlines will be increased, and consequently the pressure in the flameholder wake will be reduced.

If this is the case, the blockage ratio should have a strong effect on the flame spreading rate near the flameholder. This effect was investigated by obtaining flame width data for a constant diameter

flameholder operating at different blockage ratios. This was done by mounting the flameholder first across the 2-inch and then across the 4-inch dimension of the duct, thus, doubling the blockage ratio. The effect of doubling the blockage ratio for a 1/2 inch circular flameholder (Cf. Figure 11) is a definite decrease in flame width with increased blockage. Since this procedure also increases the aspect ratio of the flameholders, width measurements of a flame stabilized by a 1/2 inch diameter flameholder in a duct 1 inch wide and 4 inches high were made. The data indicates that the effect of increasing the aspect ratio by a factor of two is small and may be neglected.

Figure 12 shows a comparison of flame width data for three sets of two different diameter flameholders operating at the same blockage ratio. This data demonstrates that for equivalent blockage ratios, the flame width scales approximately with the flameholder diameter. There is a small difference shown in the flame widths for the flameholders mounted across the 4-inch dimension of the 2" x 4" duct. The difference is apparently systematic, with a spread in data of approximately 5 per cent between the 2 inch long and 4 inch long flameholders of equivalent blockage ratios. This spread may be due to effects of increased flameholder aspect ratio and non two-dimensional flow. However, these results show that the blockage ratio is important in fixing the flame width, or spreading rate, near the flameholder for blockage ratios as low as 0.05.

Base Pressure and Blockage Ratio

In Reference 13 Roshko has shown that the spreading of the separated boundary layer from a bluff body and the base pressure coefficient for the bluff body are closely related. This suggests that the base pressure coefficient for bluff bodies acting as flame stabilizers may be a good index of the effect of blockage ratio on the spreading of the flame. Hence, examination of base pressure coefficients for the cylindrical flameholder offers a possible means of checking the previously determined results.

Static pressures were measured at the central downstream stagnation point of the 1/8", 1/4", 1/2" and 1" diameter cylindrical flameholders mounted alternately across each dimension of the 2" x 4" duct. The results, shown in Figure 13, indicate that for flameholders operating at the same blockage ratio and Reynolds number, base pressure coefficients agree quite closely and are independent of flameholder scale and aspect ratio.

The base pressure coefficients shown in Figure 13 were obtained at stoichiometric fuel-air mixture ratio, but considerable data was taken to prove that for the interesting fuel-air ratio range, this mixture ratio has very little effect on the measured base pressure coefficients.

The rapid decrease of base pressure coefficient with increasing blockage ratio and the good agreement between different diameter flameholders operating at the same blockage ratios demonstrates that the blockage ratio is an important parameter in fixing the flame geometry.

It is interesting to note that no large change in the base pressure coefficient occurs as transition from laminar to turbulent flow takes place in the mixing zone.

Effect of Bluff Body Geometry

There appear to be two classes of bluff body flameholder which differ in the rate at which the initial part of the wake spreads. For the class of flameholder geometries and the range of Reynolds numbers investigated in these experiments, the initial spreading rate of the flame was large. Flameholder shapes such as circular cylinders, V-gutters, spheres, discs, and flat plates are included in this class for the Reynolds number range investigated. Although flames stabilized in the wake of all of these flameholder types have not been thoroughly investigated, enough data has been determined to indicate that the dependence of flame width on approach gas velocity, fuel-air ratio, and blockage ratio is similar to that determined for the circular cylinders primarily studied in this investigation.

Some preliminary studies by Zukoski of as yet unpublished data have indicated that there is another group of flameholder geometries, such as a cylinder with a conical nose or a bar with wedge shaped nose mounted parallel with the flow, for which the results reported here are not applicable. For this second type of flameholder the initial flame spreading rate is relatively small, and the effects of blockage ratio on flame geometry and base pressure coefficient appears to be negligible.

Summary and Discussion

For flameholders, such as cylinders, for which the initial flame spreading rate is large, the width of the flame depends strongly on the blockage ratio. For the initial portion of the flame, the ratio of flame width of flameholder diameter decreases rapidly with increasing

blockage ratio for blockage ratios as low as 0.05.

For this type flameholder, the dependence of flame width on approach gas speed and fuel-air mixture ratio is small for a region of many diameters downstream of the flameholder. For flameholders of different diameter operating at the same blockage ratio, the flame widths scale linearly with the diameter of the flameholder.

The strong dependence of base pressure coefficients on blockage ratio is to be expected if the increase in gas speed past the wake with increasing blockage ratio is taken into account. The gas speed past the flame increases due to the fact that flow area is reduced as blockage ratio increases. If the assumption is made that the recirculation zone is a region of constant static pressure and that Bernoulli's equation may be applied, the stream line separating the wake from the approach stream will be a constant velocity stream line. Under these conditions, it can be shown (Cf. Ref. 2) that $\sqrt{1 - C_p} = U/V$ where $\bar{U}$ is the velocity along the separation stream line, $\bar{V}$ the approach gas speed, and C_p the base pressure coefficient. A comparison of values of $\sqrt{1 - C_p}$ with experimentally determined values of the ratio U/V is given in Table I. Note that $\bar{U}$ is determined at the edge of the flame near the downstream end of the recirculation zone. The agreement of the two sets of data is excellent and clearly substantiates the conclusion that the decrease in base pressure is a blockage effect.

IV. RECIRCULATION ZONE LENGTH

Although boundaries between the recirculation zone and mixing zone are not easily defined experimentally, the downstream end point of the zone is readily determined by an elementary experimental technique. This end point is defined as the point farthest downstream from the flameholder at which gas flow in the upstream direction can be detected. Thus, the downstream end of the recirculation zone can be ideally considered as the downstream stagnation point of the wake. The length of recirculation zone, "L", is defined as the distance from the plane of maximum cross-sectional dimension of the flameholder to the end point of the recirculation zone. For the circular cylinder flameholders used in this investigation, the origin for recirculation zone lengths is the cylinder axis. Recirculation zone lengths defined in this manner were determined for a wide range of operating conditions and flameholder sizes.

Measuring Technique

The end point of the recirculation zone was determined by a flow tracer method. A 1/32" diameter probe with a stainless steel tip was used to inject a flow of salt water into the hot wake gases. This salt water evaporated at the probe exit to give a brilliant yellow sodium vapor color which moved with the wake gases. The recirculation zone end point was determined by moving the probe downstream from the flameholder axis to the point at which no sodium vapor flowed upstream.

The quantity of recirculating sodium vapor dropped off sharply

as the probe approached the end of the zone, and it was necessary to define the end point as the farthest point downstream at which yellow bursts moved upstream on the order of twice per second. The distance between this point and a point just upstream at which almost continuous upstream flow of yellow color was observed was less than 10 per cent of the total recirculation zone length.

The probe was mounted on a modified lathe compound such that the position of the probe could be determined within ± 0.05 inches, or a reading error of no more than ± 5 per cent of the total zone length. The recirculation zone lengths were reproducible within 2 to 3 per cent so that the overall error in recirculation zone length measurements was of the order of ± 5 per cent.

Velocity Effects on Recirculation Zone Length

The dependence of recirculation zone length on approach gas speed is strongly affected by the transition from laminar to turbulent flow in the mixing zone. The zone length was found to decrease as the transition range of Reynolds numbers was approached and to increase as the mixture velocity increased above the transition region. It was found, however, that for high mixture speeds, the zone length reached a constant maximum value which was no longer dependent on the mixture velocity. This approach to a maximum with increasing approach velocity is illustrated in Figure 14. Since the flow Reynolds numbers of engineering interest are in the turbulent flow regime where L is constant, the quantity "L_{max} is considered the important recirculation zone parameter.

Fuel-Air Ratio Effects

At flow Reynolds numbers below the value for transition from laminar to turbulent flow in the mixing zone, the recirculation zone length is strongly dependent on the fuel-air ratio. The results of the present work show that for fixed velocity the length is usually shortest near stoichiometric mixture ratios and longest near either blowoff limit. For gas speeds appreciably greater than the transition range, the dependence of L on fuel-air ratio is greatly reduced, although an increase in the measured value of L on the order of 5 per cent can be detected near either blow off limit.

Therefore, in the range of interest, the dependence of zone length on fuel-air ratio is small.

Effect of Blockage Ratio

The fact that blockage effects are important in fixing the wake width suggests that these effects should also be important in fixing the length of the recirculation zone. To investigate this possibility, recirculation zone lengths were measured for several different flameholder sizes and blockage ratios. This data, presented in Figure 14, demonstrates that for equivalent blockage ratios L_{max}/D is approximately the same for different diameter flameholders. To determine the effect of changing the aspect ratio of the flameholder, recirculation zone lengths were also measured using 1/4 and 1/2 inch diameter flameholders in a 1 inch wide by 4 inch high duct. The zone length data for the shorter length flameholders is included in Figure 14. It can be seen from this plot that the effect of increasing aspect ratio of the flameholder is systematic and that (L/D) increases by approxi-

mately 8 per cent for an eight fold increase in aspect ratio. However, the data is too limited to determine more than the fact that the dependence of L on aspect ratio is very weak.

The data was then examined to determine the effect of blockage ratio on the recirculation zone length. Figure 15 is the interesting result of this investigation. In this figure, L_{max} is normalized by the flameholder diameter and plotted on a logarithmic scale as a function of blockage ratio. This data demonstrates that the recirculation zone length depends very strongly on blockage ratio.

The experimental results plot very nearly as a straight line and indicate that L_{max}/D is proportional to $(D/H)^{-\frac{1}{2}}$ for the range of blockage ratios from 0.05 to 0.25. If $L_{max}/D \propto (D/H)^{-\frac{1}{2}}$, then for a constant duct height, $L_{max}/D \propto D^{-\frac{1}{2}}$, or $L_{max} \propto D^{+\frac{1}{2}}$. This is the relation found experimentally by Zukoski (Ref. 5). Therefore, the square root dependence of L, and hence of blow off velocity, on flameholder diameter is undoubtedly primarily due to a blockage effect. These results indicate, moreover, that for equivalent blockage ratios, the maximum length of the recirculation zone in the wake of a circular cylinder flameholder scales linearly with the flameholder diameter.

Effect of Flameholder Geometry

For flameholders such as "V" gutters and spheres the recirculation zone lengths also appear to approach a maximum for high flow speeds, although the range of Reynolds numbers for transition in the mixing zone is different. For these flameholder shapes the effects of velocity, fuel air ratio and blockage ratio appear to be similar to

those found for circular cylinders.

As may be expected from the discussion in section II of this report, the cone-cylinder flameholder, studied by Zukoski, appears to have recirculation zone lengths which are completely independent of gas velocity and blockage ratio. The basic difference between the circular cylinder flameholder mounted across the flow and the cylindric flameholders mounted parallel to the flow appears to be in the angle relative to the flow direction at which the initial wake spreads.

Summary

For flame holders of the circular cylinder type operating in the turbulent mixing regime, the length of the recirculation zone is substantially independent of the approach flow velocity and fuel air ratio, but is strongly affected by the blockage ratio. The latter dependence is of the form $L_{max}/D \propto (D/H)^{-\frac{1}{2}}$ for values of the blockage ratio between 0.05 and 0.25. For flame holders operating at constant blockage ratio, the zone length scales directly with flame holder diameter.

V. DISCUSSION AND CONCLUDING REMARKS

The experimental results demonstrate conclusively that for flameholders similar to the circular cylinder, the blockage ratio has a strong influence on the geometry of the immediate wake and hence on the blowoff limits for the flame holder. For a duct of fixed size, the length of the recirculation zone behind a circular cylinder flameholder is found to vary as the square root of flame holder diameter, whereas for circular cylinders operating at constant blockage ratios, the length scales directly with the flameholder diameter.

The fact that the wake width is a strong function of the blockage ratio suggests that the wake width rather than the flame holder diameter should be used as the characteristic dimension of the flameholder-duct flow system. The wake width which is most appropriate for such use is the width evaluated at $X = L$. However, due to the limited field covered by photographs, the width at this position could not be evaluated for all flameholders investigated. Furthermore, the width at this position is difficult to evaluate due to non-systematic flow disturbances which start near the downstream end of the recirculation zone. For these reasons, the width was evaluated at the point $X = L/2$.

When L_{max} was normalized by the flame width measured at a distance $L_{max}/2$ downstream of the flameholder, the ratio $L_{max}/W_{\frac{1}{2}}$ was found to be essentially independent of blockage ratio (Cf. Figure 15). The 7 per cent maximum scatter in data (Cf. Figure 15) may be attributed to the fact that two experimental measurements

with corresponding measurement errors are involved in determining the ratio. The good agreement of the data indicates that the flame width is the correct characteristic dimension and further that the mixing zone spreading rate, which fixed L, is not a function of the blockage ratio.

The basic effects of blockage ratio on the flame stabilization process are now clear. As this ratio is increased, for a given diameter flameholder operating at a fixed fuel-air ratio and a gas speed in the turbulent mixing range, both the length of the recirculation zone and the ratio (V/U) will be decreased; here V is the approach stream velocity and U is the gas velocity past the flame at a distance L downstream of the flameholder. As previously suggested, the flow parameter of engineering importance is the approach gas velocity at which the flame blows off, V_{bo}. The mechanism of bluff body flame stabilization described in the introduction indicates that U_{bo} L_{max}. Therefore, it follows from the identity: $V_{bo} = (V/U)\, U_{bo}$ that V_{bo} $(V/U)\, L_{max}$. Thus, as the blockage ratio is increased, the velocity of the approach gas stream at which blow off occurs is reduced by a decrease in both L_{max} and the ratio (V/U). While the reduction of the ratio V/U with increased blockage has been previously considered, the fact that blockage also directly affects the flame stabilization mechanism, i. e., by affecting L_{max}, has not been appreciated. These blockage effects are directly responsible for the observed square root dependence of blow off velocity on flame holder diameter in a constant height duct.

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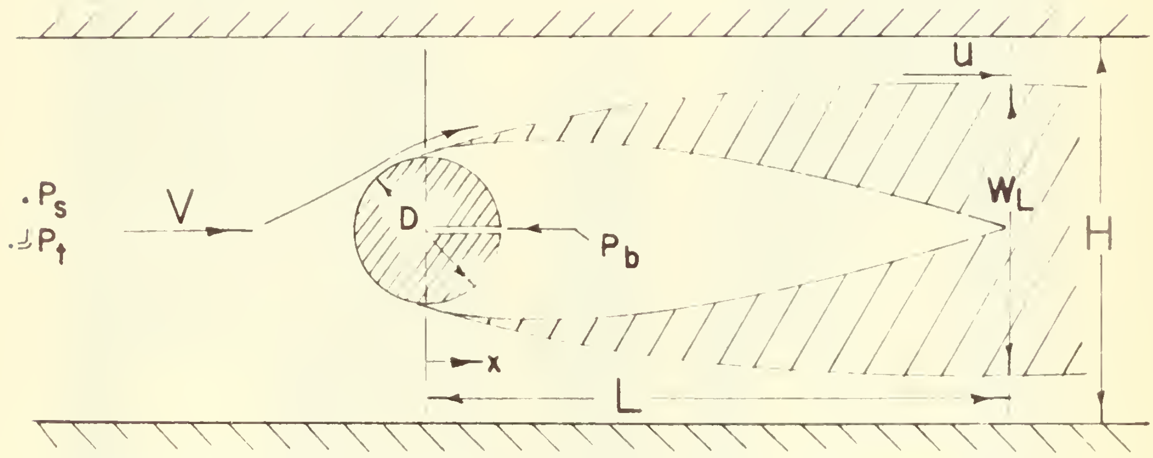
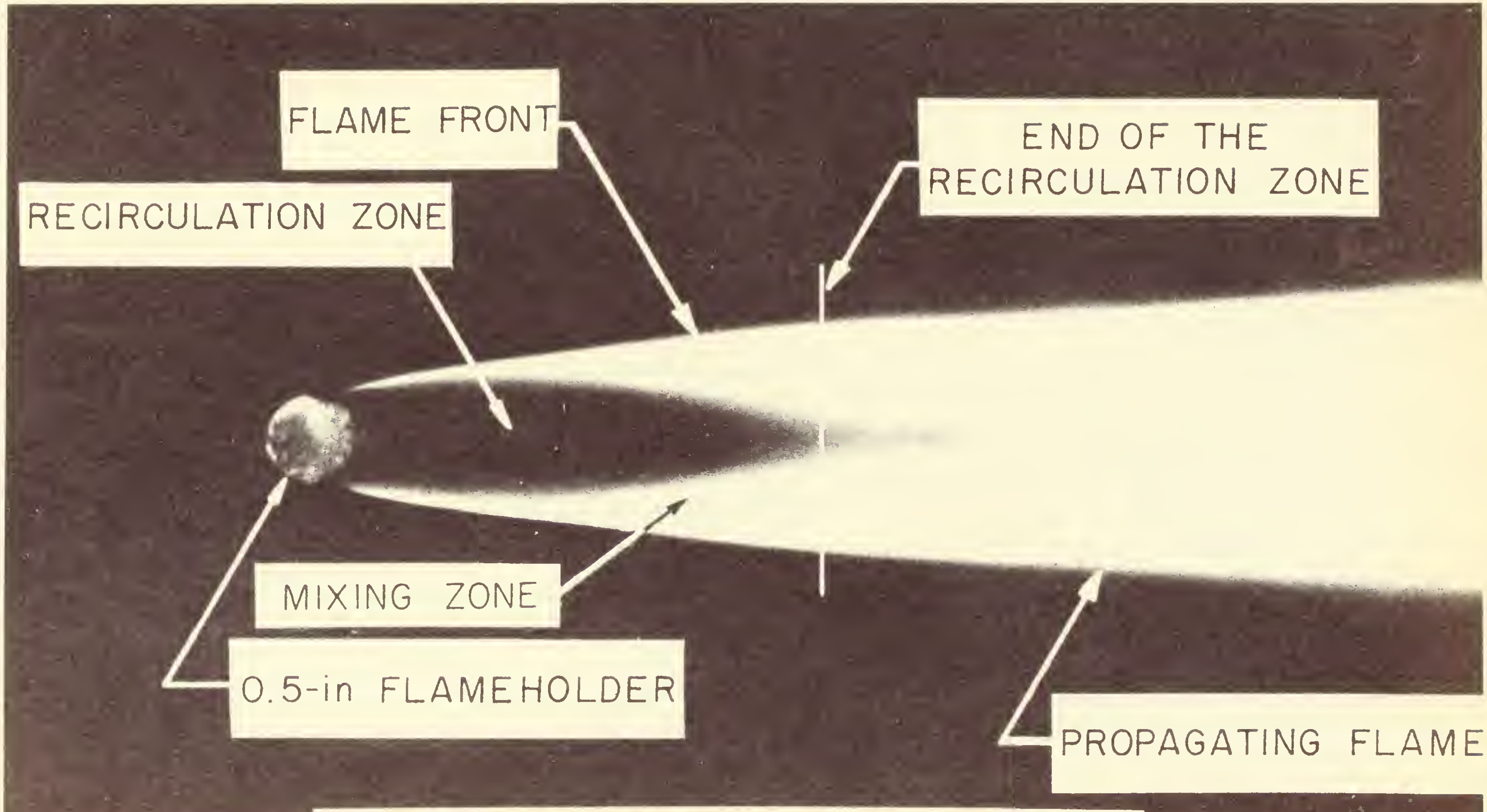
TABLE I

COMPARISON OF EXPERIMENTAL RESULTS FOR THE RATIO $\frac{U}{V}$ AND $\sqrt{1 - C_p}$; $R_e \doteq 10^4$

D	$\frac{D}{H}$	$\sqrt{1 - C_p})_{exp}$	$\frac{U}{V})_{exp}$
1/8"	1/32	1.14	1.10
1/4	1/16	1.21	1.17
1/2	1/8	1.28	1.27
1	1/4	1.47	1.50



SKETCH OF TEST SECTION INDICATING PARAMETERS


FLAME FRONT
RECIRCULATION ZONE
END OF THE RECIRCULATION ZONE
MIXING ZONE
0.5-in FLAMEHOLDER
PROPAGATING FLAME

[illegible] 1. [illegible] cylinder

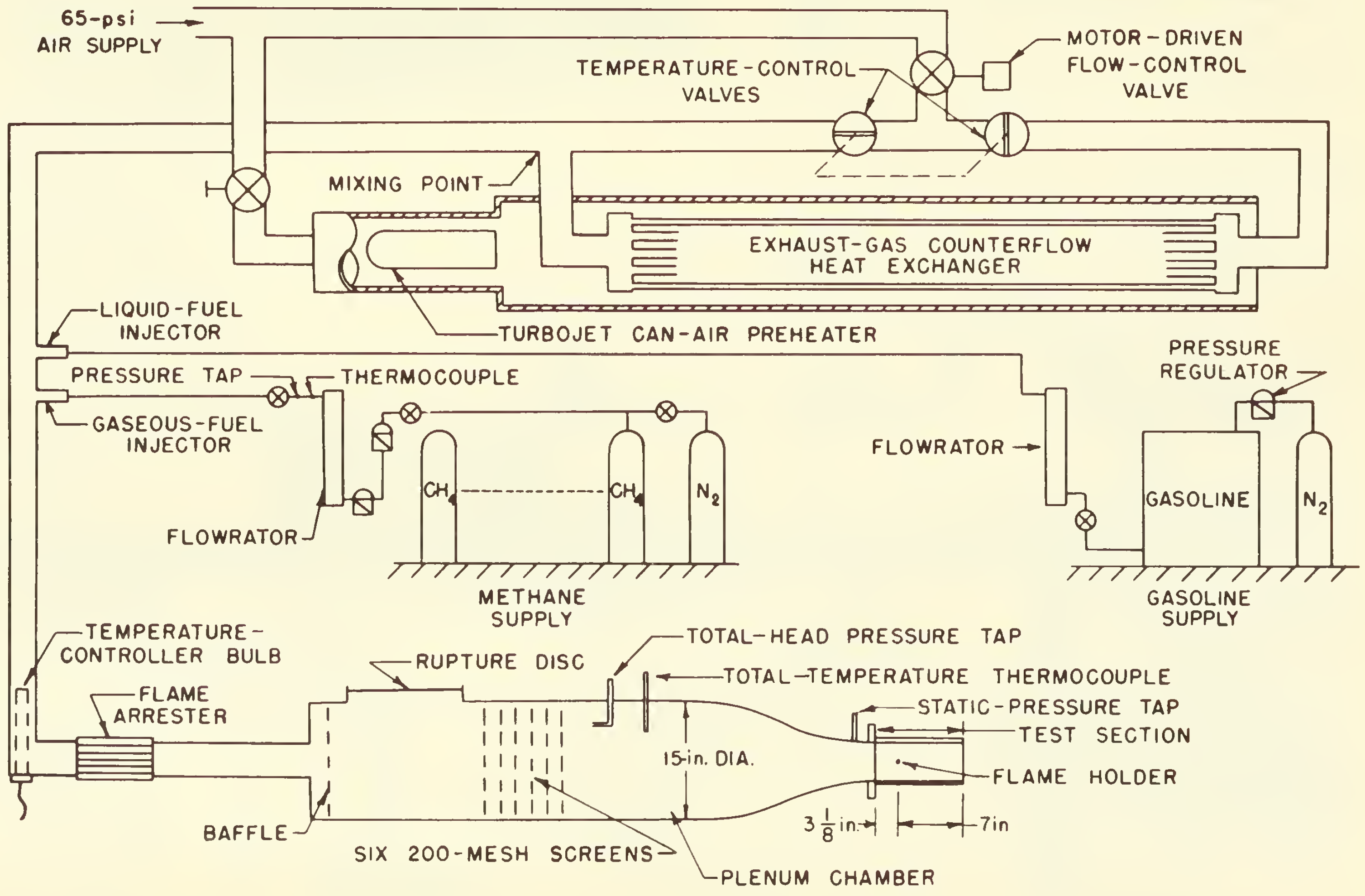
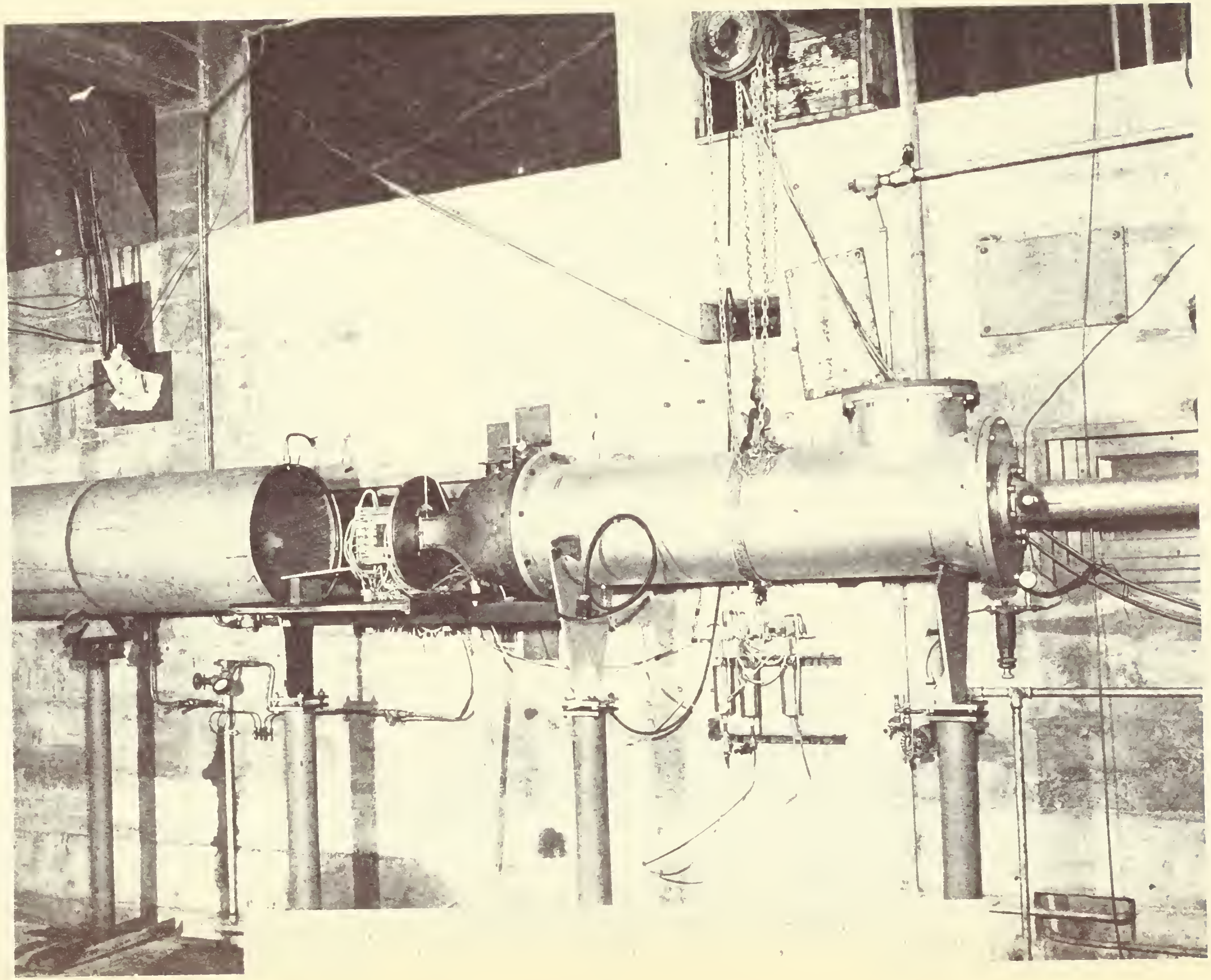


Figure 2. Schematic Diagram of Flow Systems



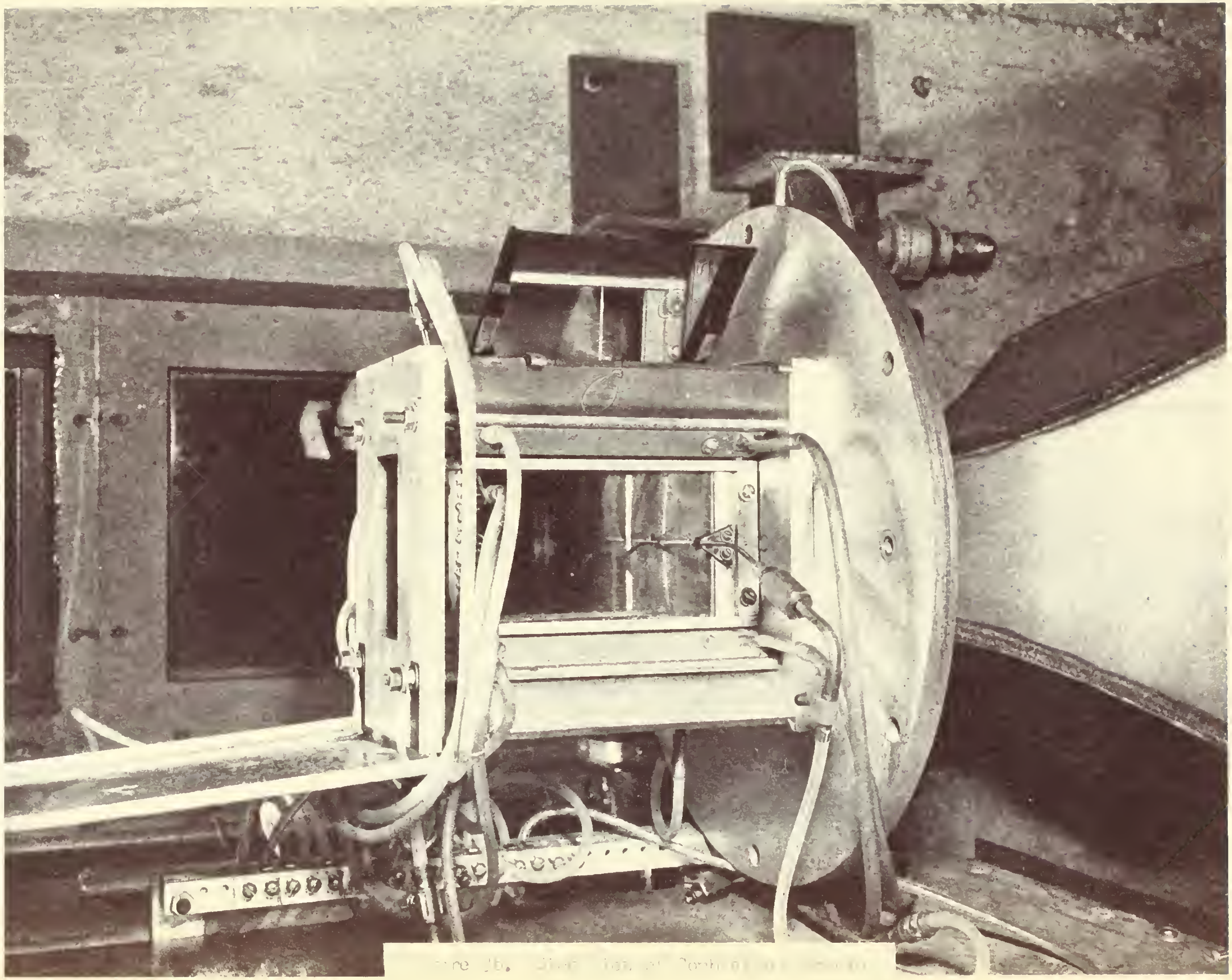


Figure 26. Close View of Combustion Section

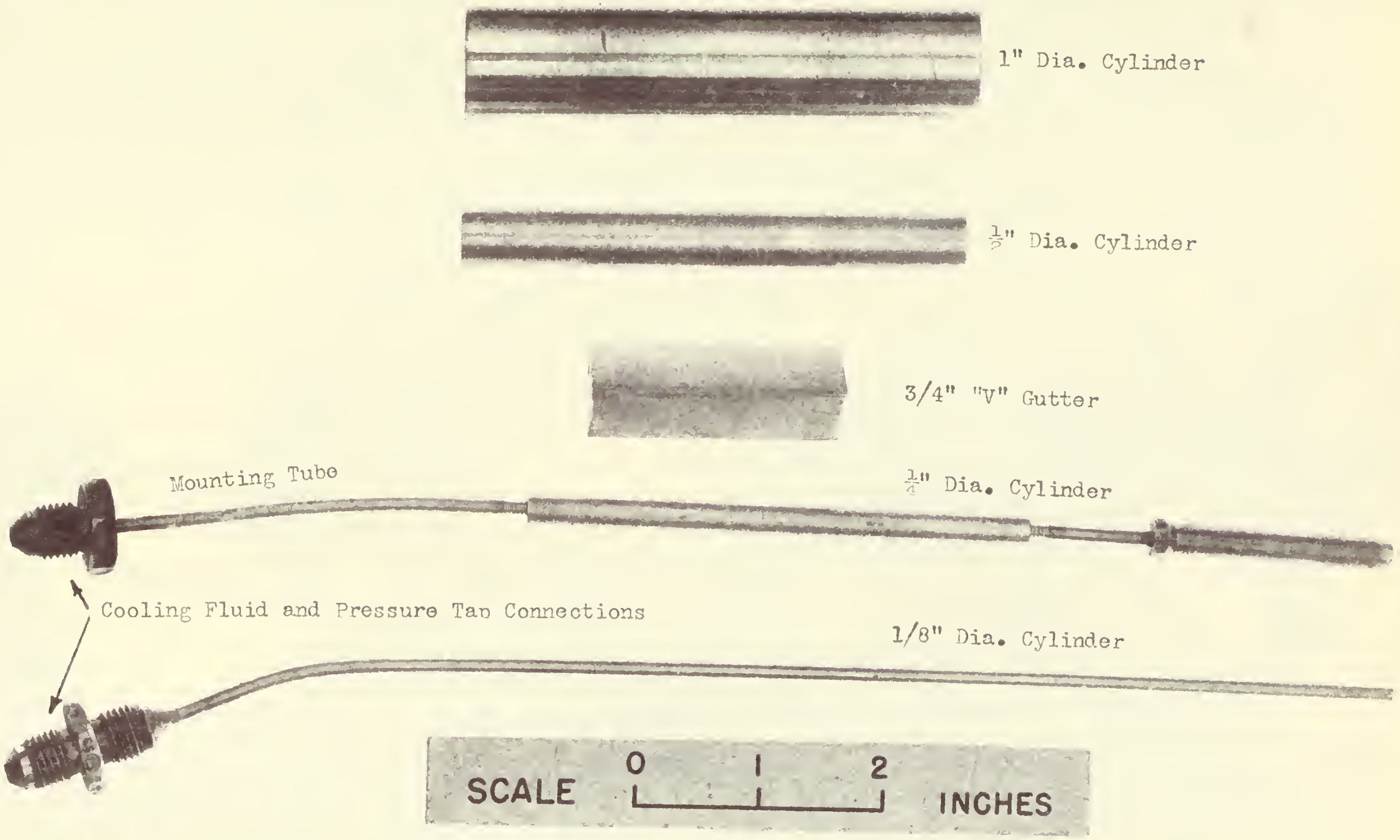
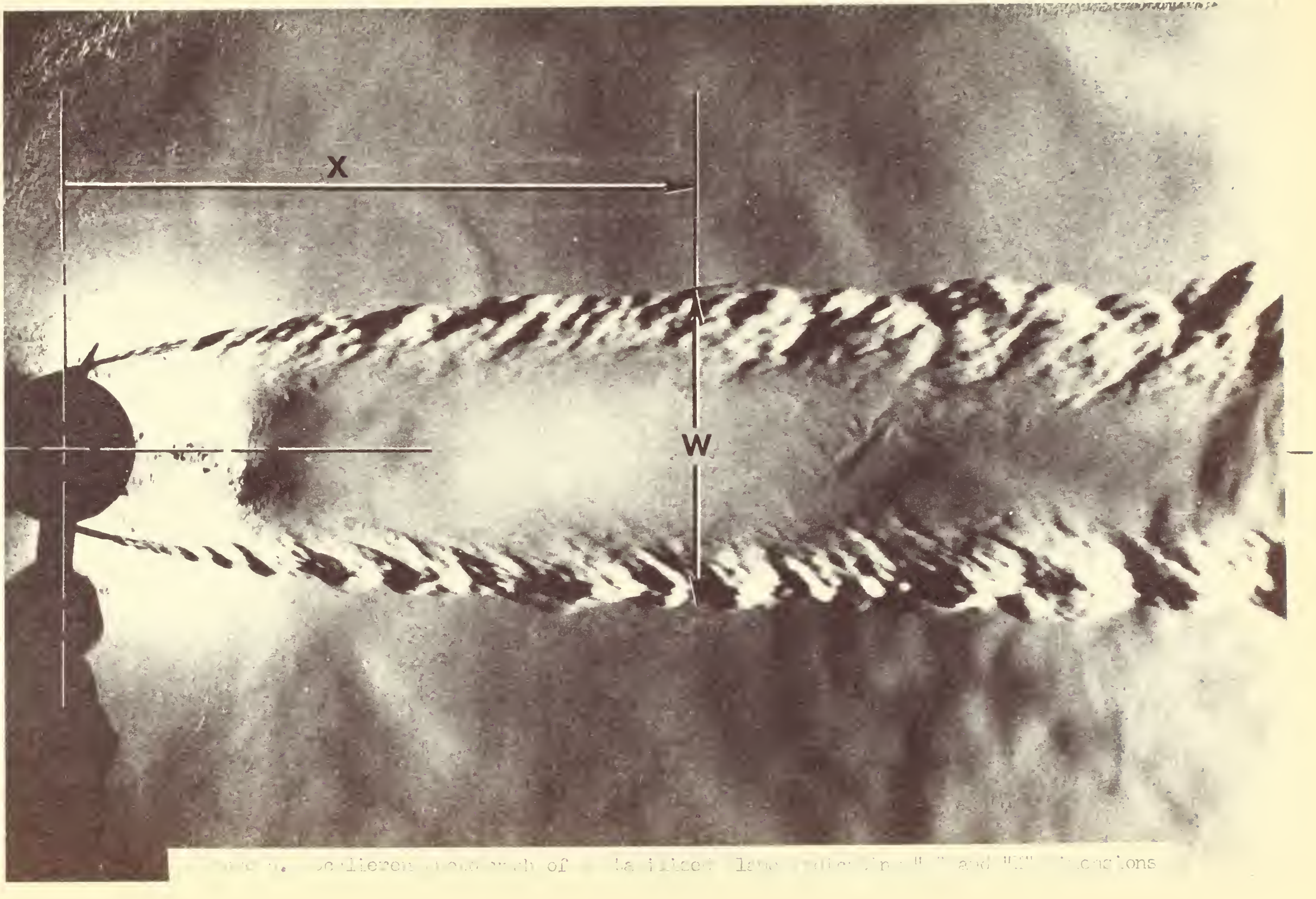


Figure 4. Photograph of Typical Flameholders Used



[illegible] Schlieren photograph of a stabilized flame indicating "X" and "W" dimensions

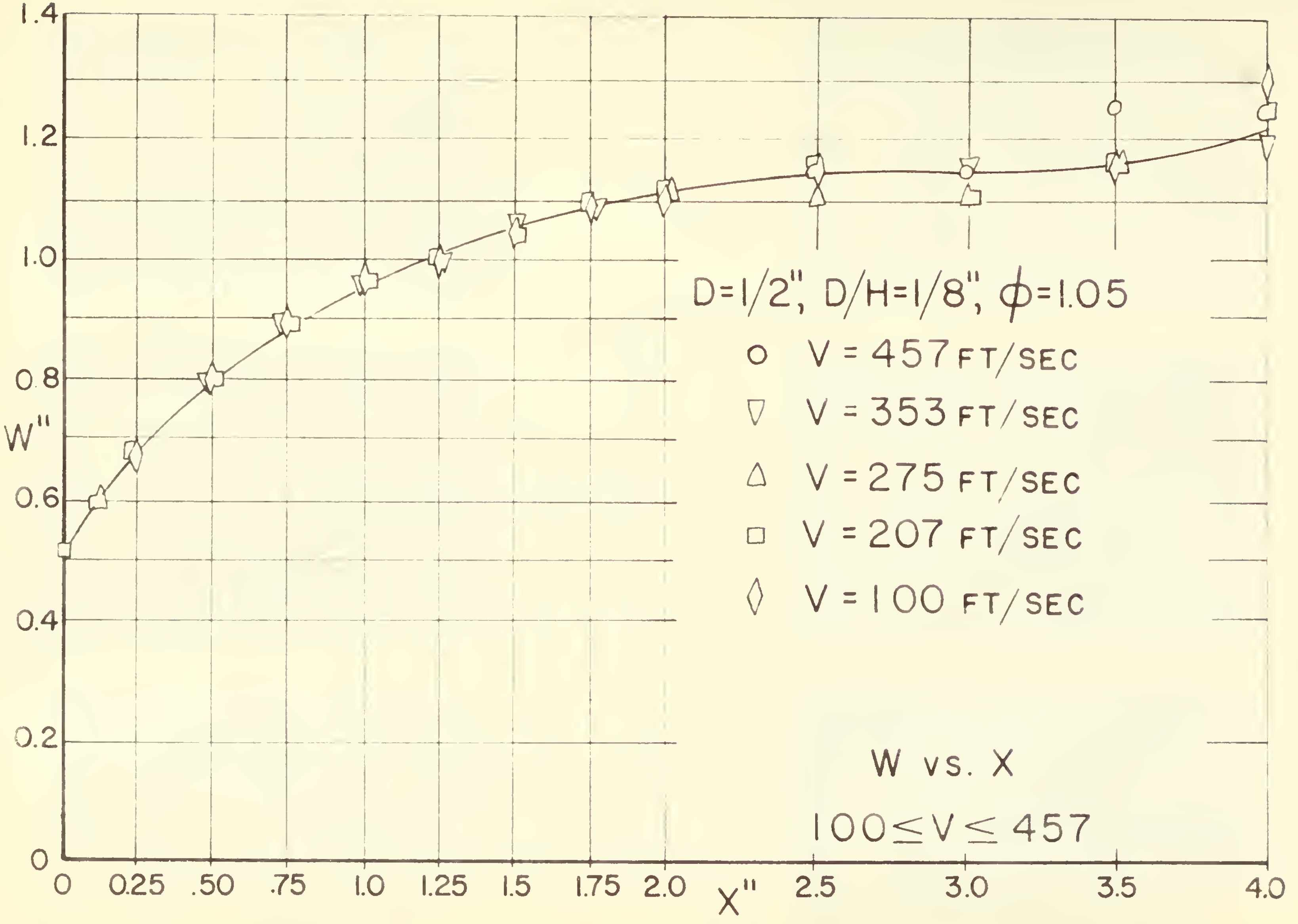
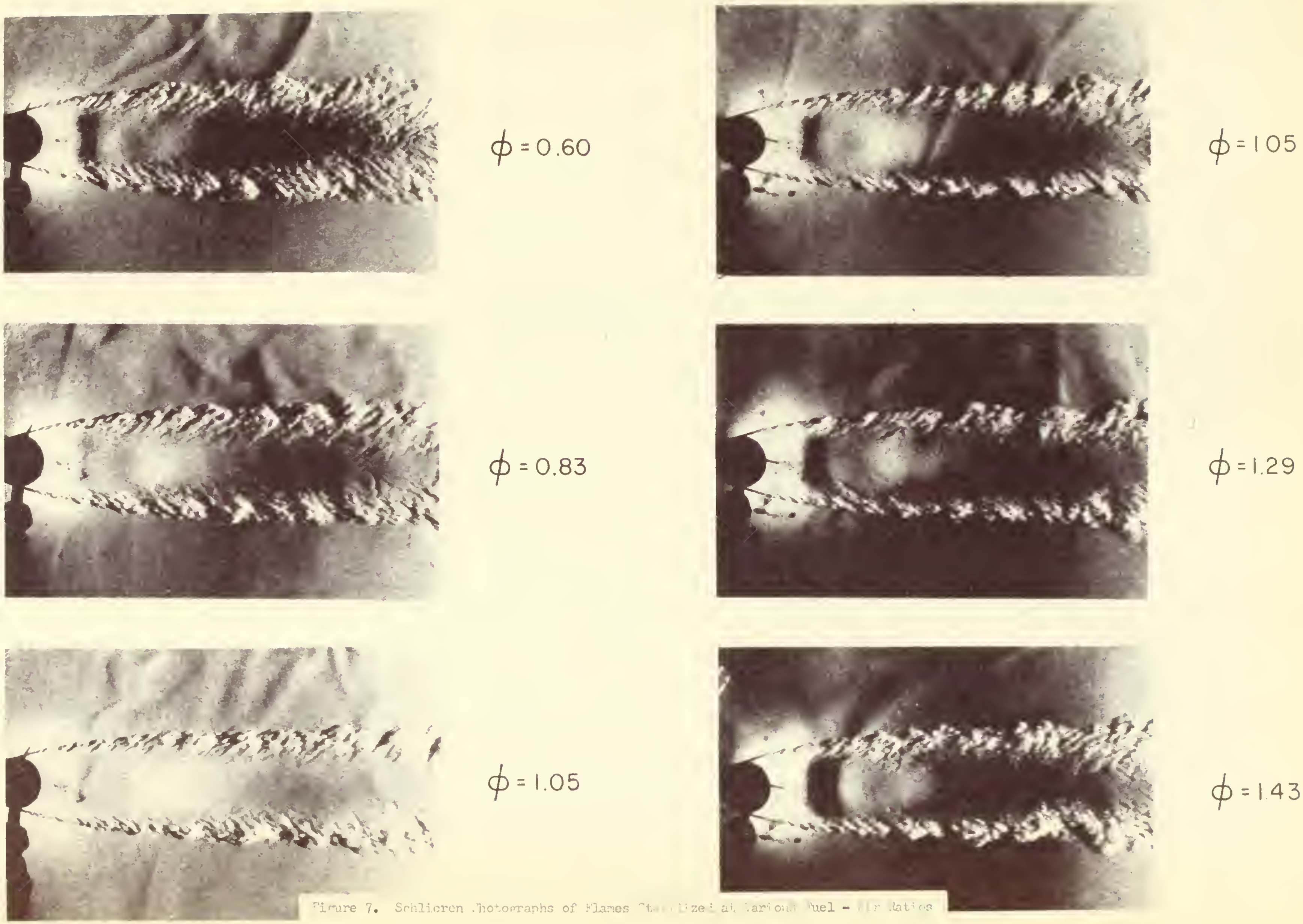


FIGURE 6
PLOT SHOWING INDEPENDENCE OF FLAME WIDTH ON APPROACH GAS VELOCITY



$\phi = 0.60$

$\phi = 0.83$

$\phi = 1.05$

$\phi = 1.05$

$\phi = 1.29$

$\phi = 1.43$

Figure 7. Schlieren Photographs of Flames Stabilized at Various Fuel - Air Ratios

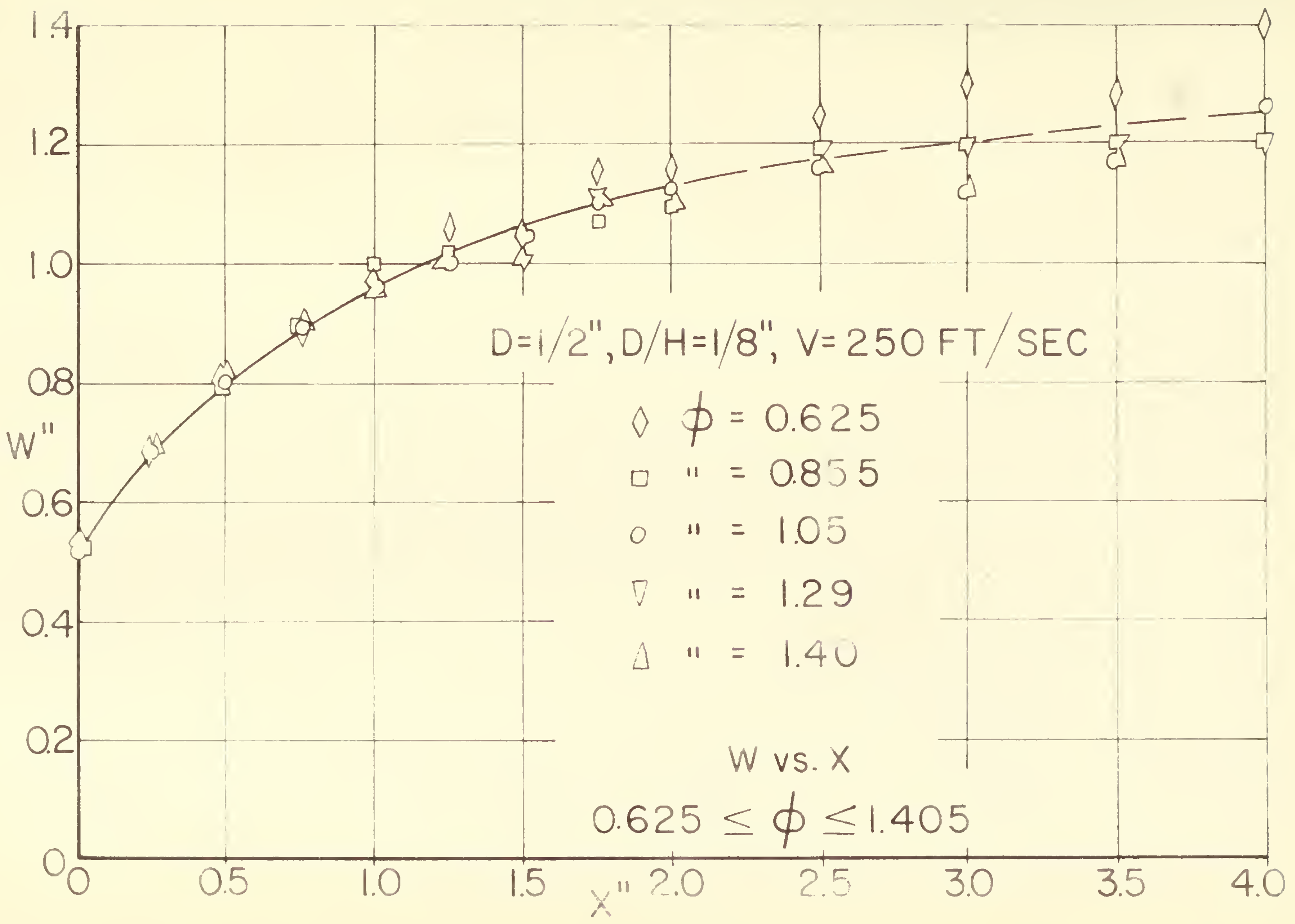


FIGURE 8
PLOT SHOWING INDEPENDENCE OF FLAME WIDTH ON FUEL-AIR RATIO

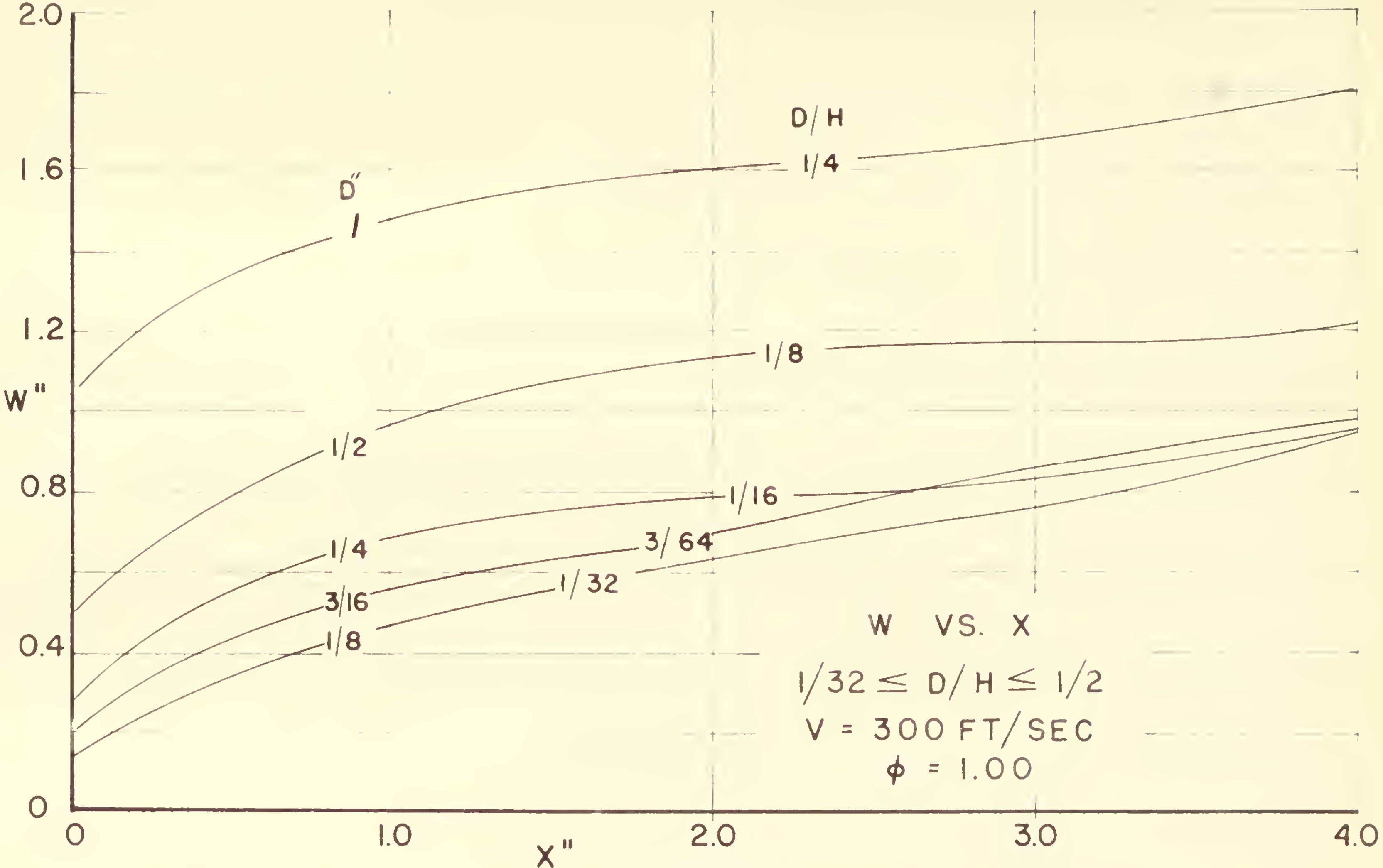


FIGURE 9
PLOT OF FLAME WIDTH DOWNSTREAM FOR DIFFERENT SIZE FLAME HOLDERS

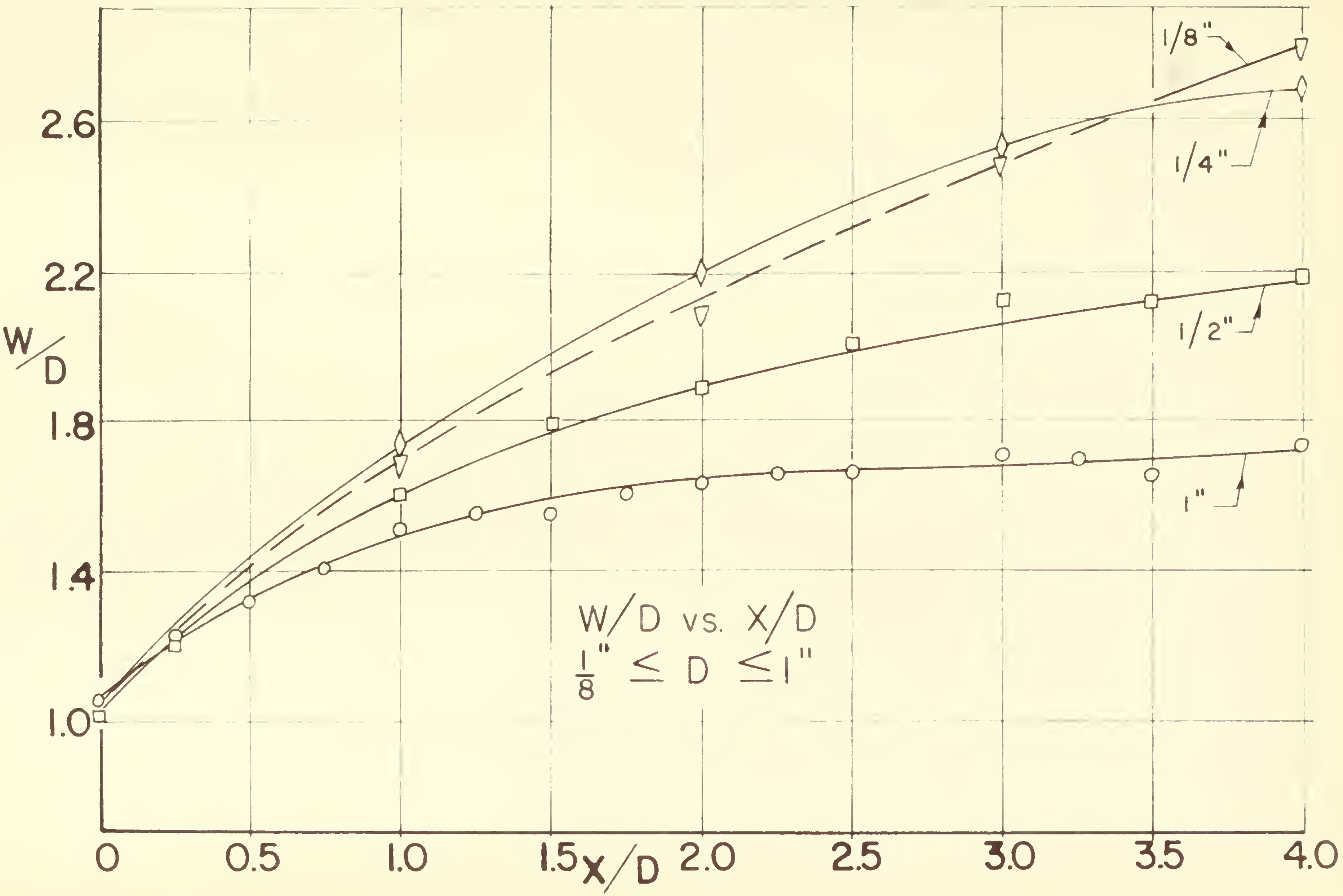


FIGURE 10
PLOT SHOWING THE EFFECT OF FLAME HOLDER DIAMETER ON THE NORMALIZED FLAME WIDTH

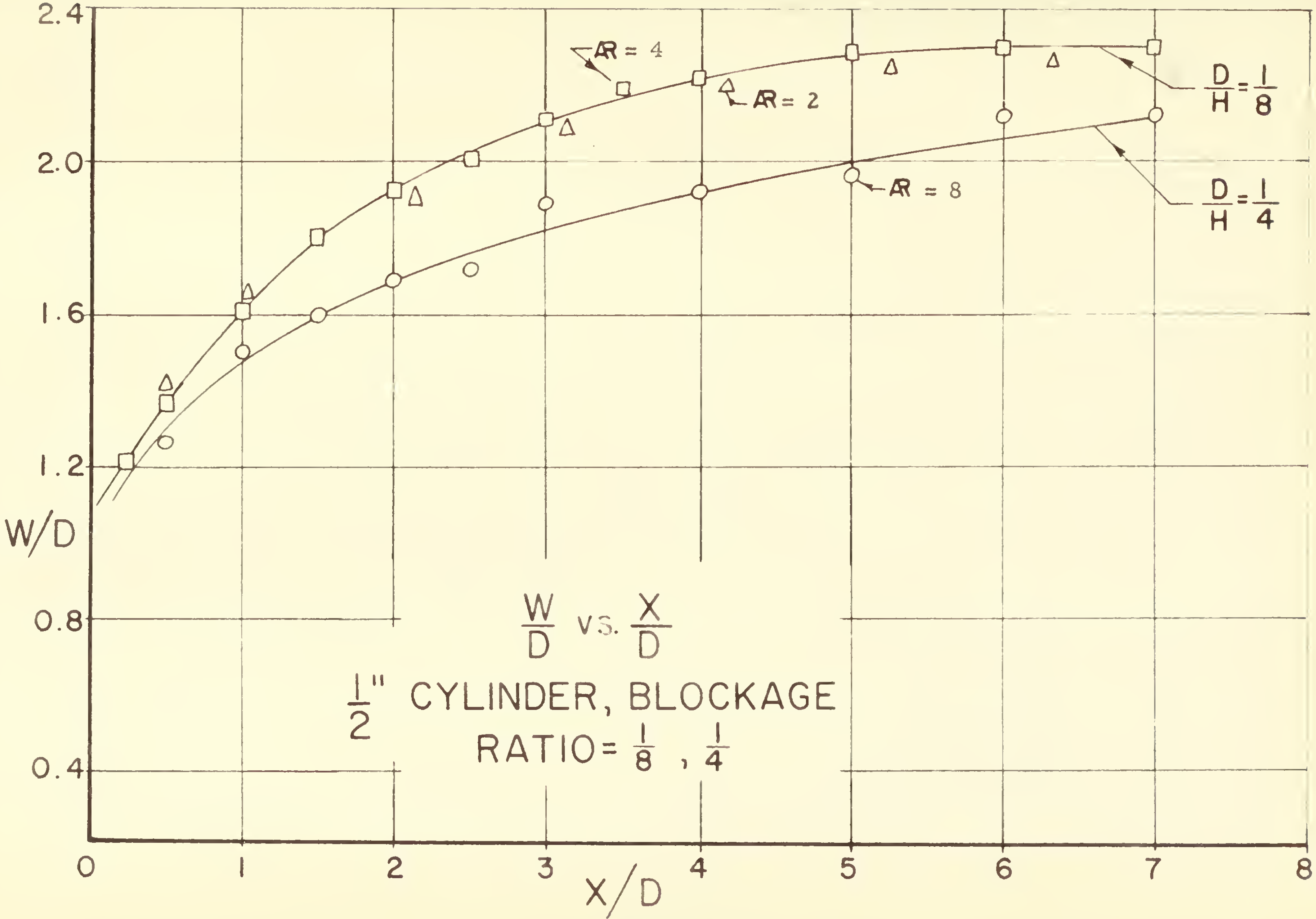


FIGURE 11
PLOT SHOWING THE EFFECT OF DOUBLING THE BLOCKAGE RATIO ON THE FLAME WIDTH

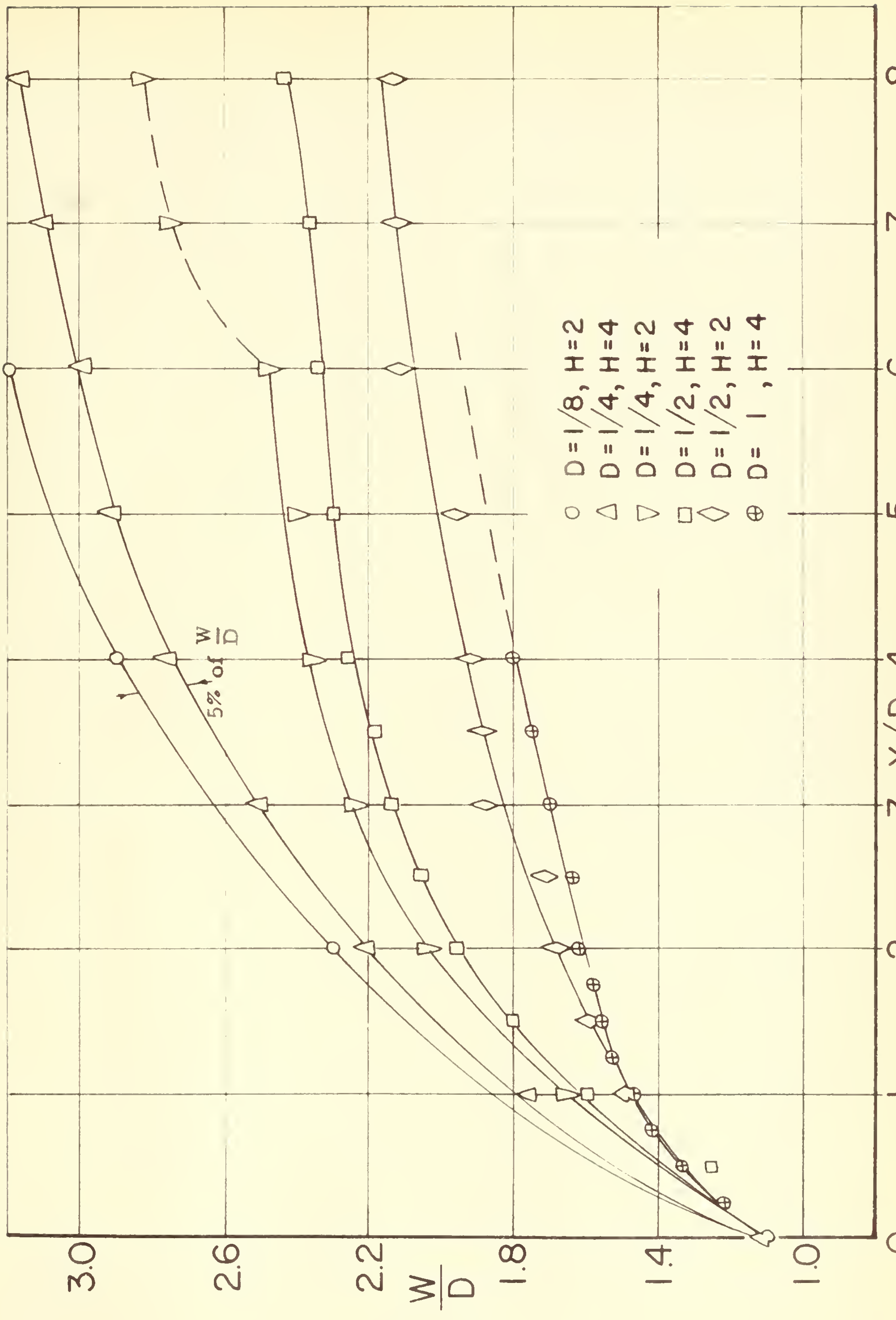


FIGURE 12
PLOT SHOWING THE EFFECT OF BLOCKAGE RATIO
ON NORMALIZED FLAME WIDTH

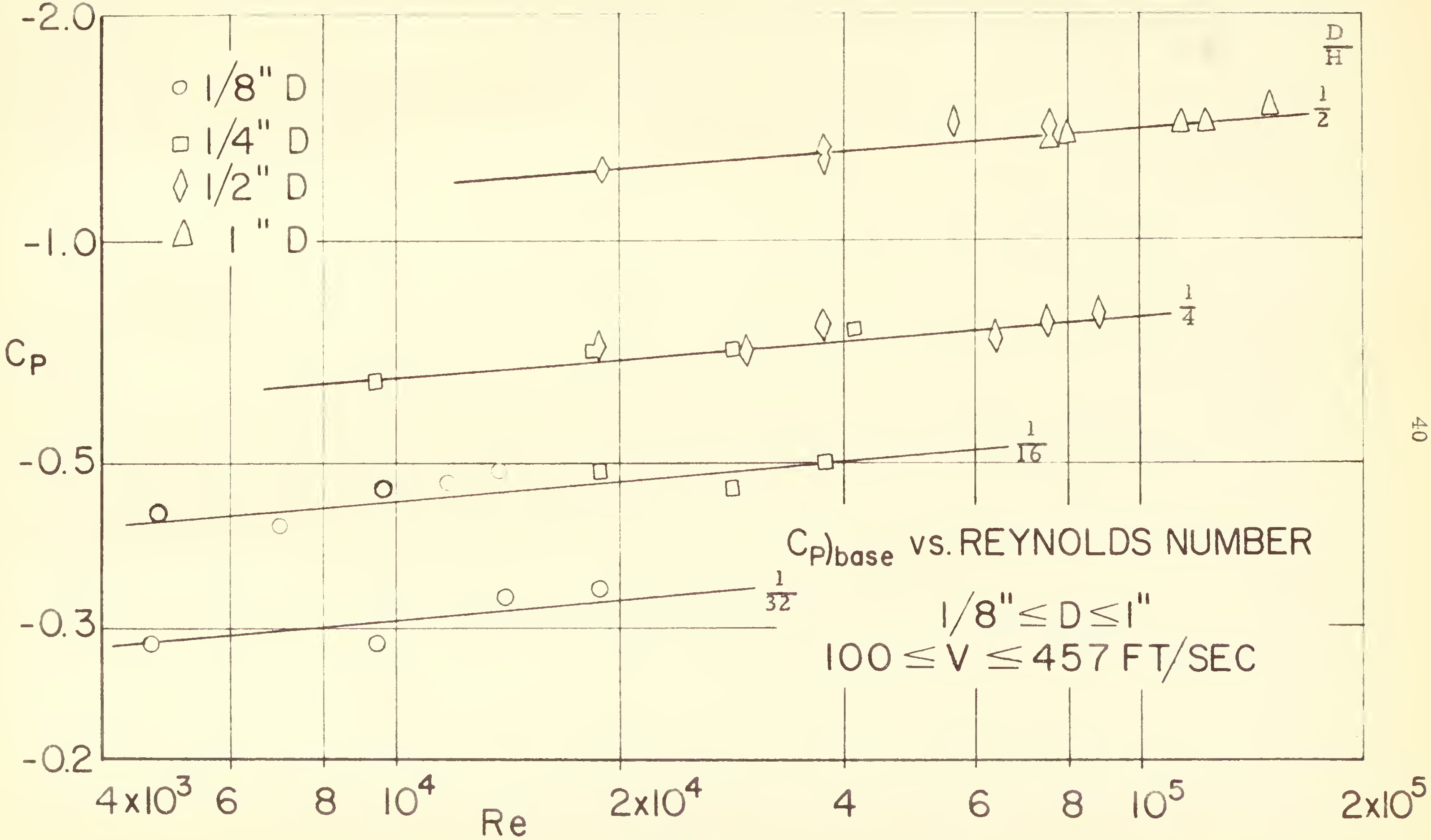


FIGURE 13
PLOT SHOWING THE DEPENDENCE OF BASE PRESSURE COEFFICIENT ON FLOW REYNOLDS NUMBER FOR DIFFERENT BLOCKAGE RATIOS

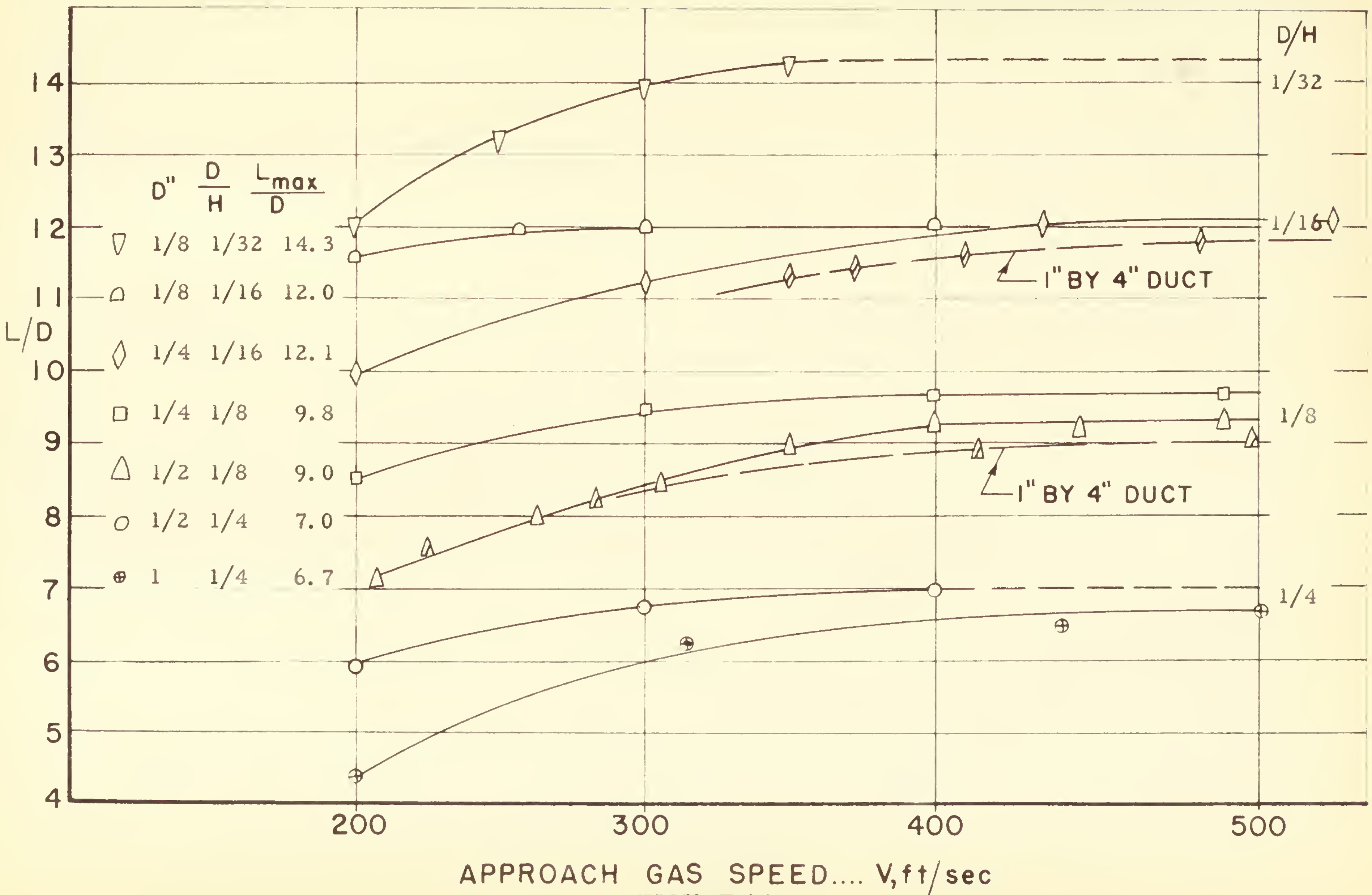


FIGURE 14
PLOT OF RECIRCULATION ZONE LENGTHS AS A FUNCTION OF APPROACH GAS VELOCITY

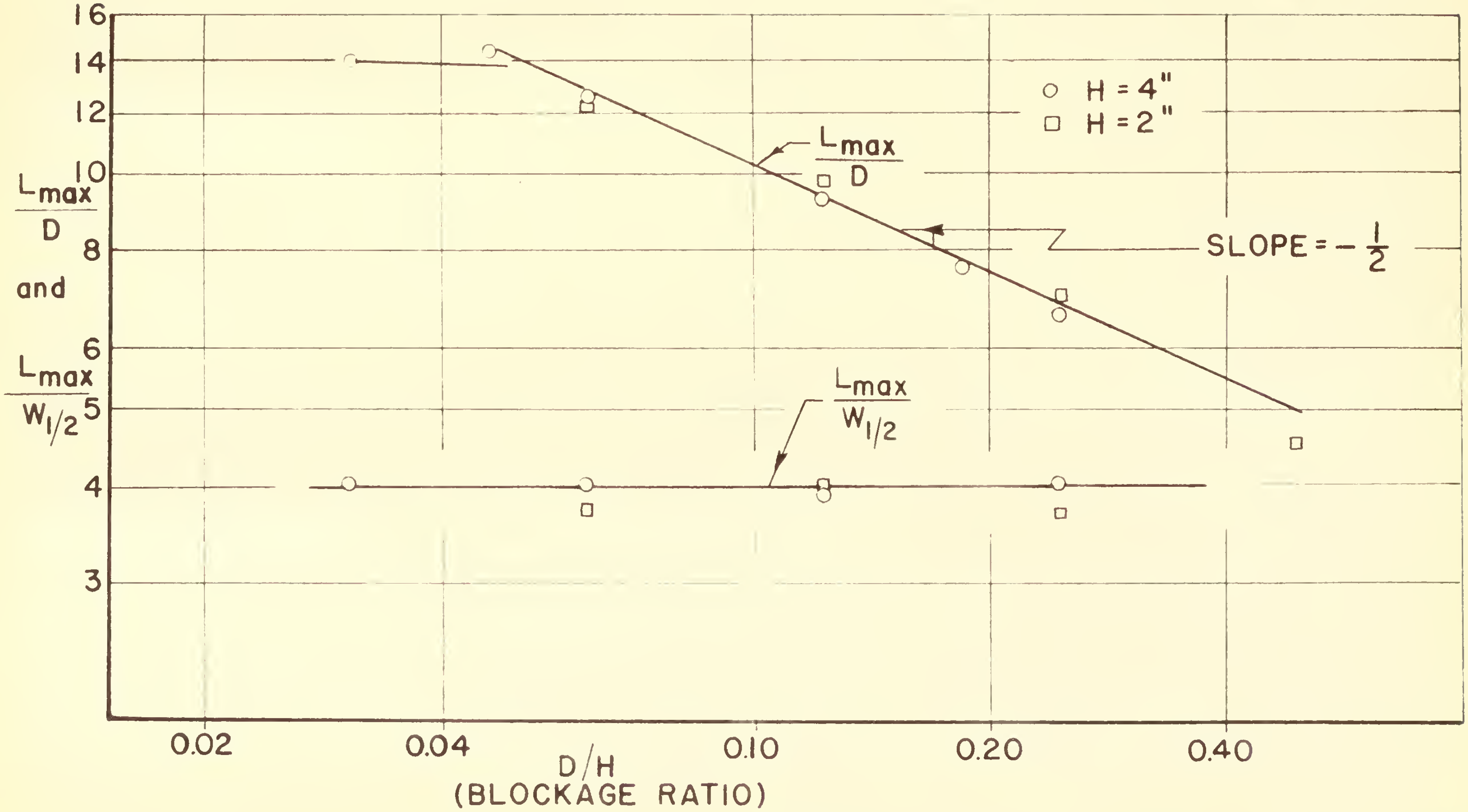


FIGURE 15
PLOT SHOWING THE EFFECT OF BLOCKAGE RATIO ON RECIRCULATION ZONE LENGTH

Thesis
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Effects of combustion chamber blockage on bluff body flame stabilization.

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